Battery Management System Performance Enhancement using Charge Equalization Controller Design

1st Ali Ashraf Ali Sallam,
dept. of industrial electronics and control,
Faculty of electronic engineering in Menouf,
Menoufia University,
Menoufia, Egypt,
ali.ashraf@el-eng.menoufia.eg

2nd Essam Nabil
dept. of industrial electronics and control,
Faculty of electronic engineering in Menouf,
Menoufia University,
Menoufia, Egypt,
essam.abdelaziz@el-eng.menofia.edu.eg

3rd Abdel-azim Sopieh
dept. of industrial electronics and control,
Faculty of electronic engineering in Menouf,
Menoufia, Egypt,
abdazimsopeh@gmail.com

***Abstract*- A precision model of a battery charge equalization controller (BCEC) is developed in this research paper to control a series-connected Li-ion battery with a number of cells (n). The BCEC's main task is to manage each cell individually by monitoring and balancing all cells by charging the over-discharged cell or discharging the overcharged one. An intelligent fuzzy logic controller (FLC) and a single sliding mode controller (SSMC) are evolved to activate bidirectional cell switches and regulate a chopper circuit's direct current (DC-DC flyback converter) with PWM generation. The model can be implemented in electric vehicle (E.V.) applications to get benefit from the Li-ion battery. It consists of individual models of an E.V., cells of Li-ion battery, a fly-back converter, and a charge equalization controller for charging and discharging are integrated with n series-connected cells of Li-ion battery. The simulation results confirm that the proposed schemes have achieved enhanced performance with balancing the Li-ion cells as the state of charge (SOC) difference between cells is maintained to be 0.1% while maintaining the battery operation with a safe region. The BCEC is compared with the existing controllers based on efficiency, power losses, performance, and cost and has achieved better results.**

Keywords: Modeling, Control algorithm, Fuzzy logic control, Sliding mode control, Charge equalization controller, State of charge, Electric vehicle, Li-ion Battery, Sustainable energies.

I. INTRODUCTION

Traditional vehicles are operated with a combustion engine with fossil fuel as a primary source with its environmental problems with the risk of shortage soon. Hence, great efforts seek to develop the usage of green energy with pure electric vehicles efficiently. According to the energy stored in the battery packs, Electric vehicles are operated, and the ultimate energy source is the electricity supplied from the generating plant [1]. Due to the importance of the electric vehicle (E.V.), too many contributions have been shared to develop a battery pack for E.V. to provide a long-lasting and high total energy storage capacity [2]. The Li-ion battery is one of the most recommended battery types used in E.V., Comparing it with the other battery types in terms of characteristics and performance, the Li-ion battery is the best one. Li-ion batteries are featured by excellent energy density, long lifetime, and are Eco-friendly, thus have found wide application in the area of consumer electronics [3]–[7]. However, it has a lot of benefits, cells of li-ion batteries have the drawbacks of low voltages and capacities. The cells have to be packed in series and parallel to meet the energy and power requirements of E.V. [8]. Despite that, it has some shortcomings that overcharged cell has a hazard of an explosion, the undercharged cell has impacted the battery life cycle, and the unbalanced charge reduces overall capacity. Thus, a Battery Management System (BMS) is vital to improving the battery's performance, lifetime and safety by maintaining the cells' state of charge (SOC) in a safe region and the cells to be balanced together[9], [10]. Thus, the BMS helps perform battery charge equalization. The model development of a battery charge equalization controller (BCEC) for managing the E.V. li-ion battery storage system is a decisive matter to keep the E.V. battery storage system at protected and equalized conditions [11]. The battery equalization algorithms are classified based on voltage [12] or based on the SOC equalization algorithm [13], [14]. The first one is easy to be used according to the ease of measuring the cell voltages but unfortunately, it can't estimate the unbalance that occurred internally between the battery cells in the battery pack as the battery voltage describes the external features that aren't able to wholly describe the battery pack’s capacity and its internal resistance. In comparison, the other one has been proposed to develop the battery inconsistency and achieve optimal battery configuration. It describes the battery's whole performance that is affected by the current and voltage of the battery, surrounding temperature, and the battery's internal resistance. The battery equalization is categorized into two methods, dissipation and non-dissipation one according to the equalization circuits. The dissipation method [15], [16] is to achieve equalization by consuming the excess capacity through energy-consuming components like resistors. Its circuit structure is simple but isn't used for its equalization time; the loss of equalization energy stored in the overcharged cells is lost as heat [17], which may cause a thermal management issue. The other method, the "non-dissipation" method [10], [18], is more efficient as it achieves equalization between cells depending on energy storage components. Those components are generally capacitors, inductors, or transformers. Several studies have been done on passive and active BCEC to balance series-connected Li-ion battery cells' charges. The resistor current shunt BCEC [19] is simple and easy in construction and implementation, but it wastes power into heat and extends the equalization process. Based on active components like capacitors, inductors, and transformers, active BCEC is used to transfer the extra charges between the cells from the overcharged one to the others or to support the balancing current to an over-discharged cell from the others. The switched capacitor BCEC [20] is also accessible to execution which shuttles the energy from one cell to another; however, it produces a current ripple and prolongs the equalization process. The multi-winding transformer BCEC [21] is useful in equalization, but it has a large magnetizing loss, design complexity, and high-costly profile. The resonance converter BCEC [22] has a high balancing speed with great efficiency; however, it has high voltage stress, design, and implementation complexities. The buck-boost converter BCEC [22], [23] is excellent in equalization, efficiency, and modularized bidirectional design. Nevertheless, it is costly and complicated in design and control. The existing BCECs are serving the current facilities in E.V. storage management. However, they suffer some common problems such as prolonging in equalization, voltage/current stress, poor efficiency, the necessity of heat management, control, and design complications. Hence to develop an efficient model for BCEC is needed to be researched at present concern. BCEC based on Fly-back, Resonant, and Buck-Boost converters, is suitable in E.V. applications with different topologies. These BCEC can achieve fast balancing speed in charging and discharging with excellent efficiency and, in contrast, require a complicated control with a complex design and are costly. To increase the battery lifetime and prolong the batteries' safety, the SOC would be monitored in real-time. Unfortunately, the SOC can't be measured directly, but many techniques are used to estimate it [24]–[26]. Among these approaches, the most used one, due to its high accuracy, besides self-corrective ability, is the model-based one [27], [28]. The SOC and open-circuit voltage (OCV) relationship is an essential parameter of the battery for many approaches like accurate battery modeling, analytical electrode materials, and reliable SOC estimation [29], [30].

In this paper, the proposed scheme may contribute to solving some of the existing problems with the E.V. li-ion battery storage management as it's simply designed to monitor a number of n cells of li-ion battery for protecting the cells from being over-discharged or over-charged and maintaining an equalization between them. The proposed scheme utilizes a bidirectional DC-DC converter to transfer the battery cells' energy to achieve equalization and keep each cell in the safe region without over-charging or over-discharging. As a result, an intelligent fuzzy logic control technique and a single sliding mode control are introduced in this paper to control the bidirectional cell switches and control the flyback converter circuit's direct current with PWM generation. This proposed model of BCEC is fewer design and execution complexities, excellent efficiency, comparatively high equalization speed, stable control, and is easy to be modified with a specified number of cells.

This paper is organized as follows: charge equalization controller algorithm is described in Section II, and in Section III Fuzzy Logic Control for SOC-based equalization is described, followed by Single Sliding Mode Control for SOC-based equalization in Section IV. The results and the comparison are in Section V. Finally, concluding remarks are made in Section VI, followed by the list of references.

II. CHARGE EQUALIZATION CONTROLLER ALGORITHM

In this paper, a nominal Li-ion battery of 15.5 Ah and 3.7 V [31], [32]. That's preferred in E.V. applications as it has an excellent output rating. Because of its essential step to evolve an accurate model of BCEC, modeling the li-ion battery to implement the equalization and obtaining the optimal power rating. As the generic model [33] is easy to be configured at any Li-ion value, it's applied for the Li-ion battery [34]. The generic model is very similar to the Shepherd model, but its advantage is that it's free from the problems of the algebraic loop, which is the problem of the Shepherd model. It's also available to perform the balancing operation to improve its performance as this model can be applied on charging and discharging as follow:

Li-ion battery charging model:

$$\mathrm{Vch} = \mathrm{Ao} - \mathrm{P}\,\frac{C}{C' + 0.1\,C}\,.\,i^{*} - \mathrm{P}\,\frac{C}{C' - C}\,C' + X\,e^{-YC'} - r.\,i \quad (1)$$

Li-ion battery discharging model:

$$\mathrm{V\,dis} = \mathrm{Ao} - \mathrm{P}\,\frac{C}{C - C'}\,.\,i^{*} - \mathrm{P}\,\frac{C}{C - C'}\,C' + X\,e^{-YC'} - r.\,i \quad (2)$$

where V_{ch}: the charging battery voltage (V).

V_{dis}: is the discharging battery voltage (V).

A0: the constant battery voltage (V).

r: the battery internal resistance (ohm).

P: the battery polarization constant (Ah-1).

i: the current of the battery (A).

C0: the current capacity (Ah), that is, Rt0 a(t)dt.

C: the maximum capacity of the battery (Ah).

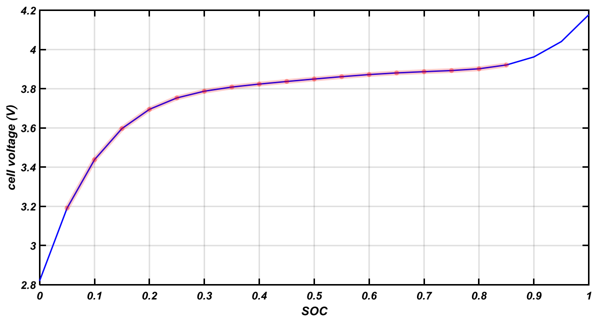
X: the exponential Battery Voltage (V).

Y: the exponential battery capacity (Ah-1).

if*: the current at low-frequency (A).

The nonlinear equation linking OCV based on the exact SOC of the Li-ion battery is represented in equation (3), and the evaluation of the Li-ion battery as a relation between the OCV and SOC is shown in Figure (1).

$$VOC = 21.049 * SOC^5 - 57.837 * SOC^4 + 62.228 * SOC^3 - 32.997 * SOC^2 + 8.9149 * SOC + 2.82. \quad (3)$$



The battery discharge characteristic curve is shown in Figure (٢).

Figure (1) The relationship between OCV and SOC of Li-ion battery.

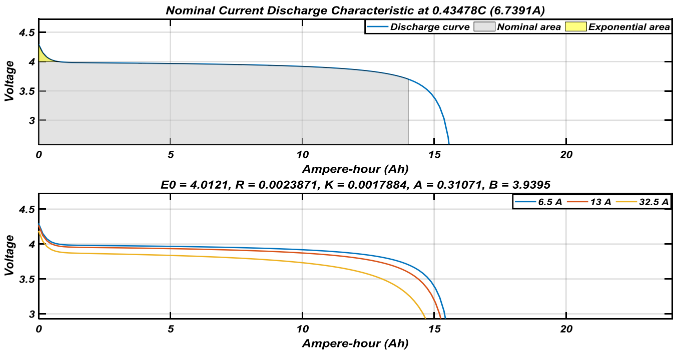


Figure (2) Battery discharge characteristic curve.

In this paper, it's decided to use a cell-to-cell non-dissipative equalization configuration here as it can achieve the balancing quickly and efficiently [35]. Our BCEC model composes of five main parts: a fly-back bidirectional converter circuit, series-connected li-ion cells of number n, an equalization control function, bidirectional battery MOSFET switches, and a converter access relay, as shown in Figure (3).

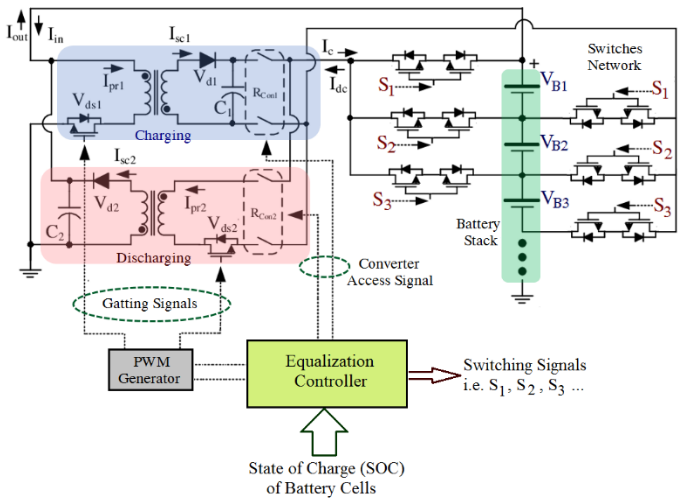
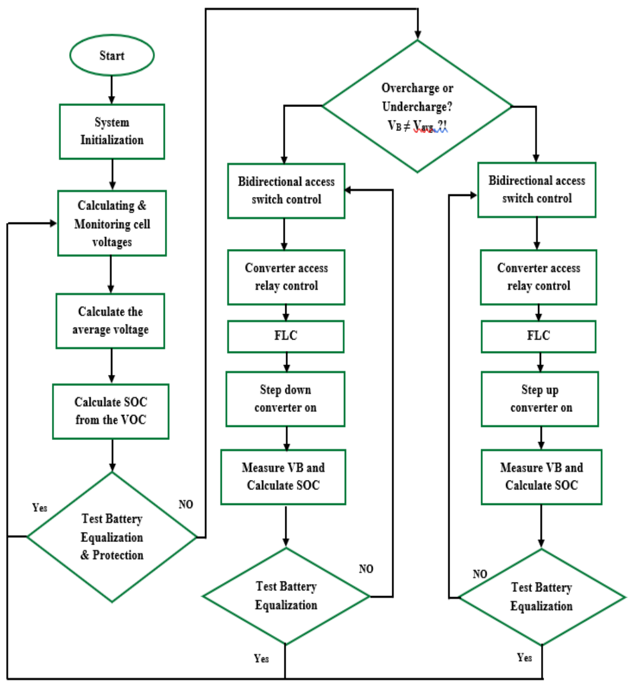


Figure (3) The BCEC model

By controlling the bidirectional battery switch and the converter access relay, we can confirm the controlled pathway between the battery stack and the battery alone for the individual to be charged or discharged through the flyback converter to achieve equalization between the cells. The controller also monitors all cells' conditions and controls the switches according to the charge equalization control algorithm. The control algorithm, which is embedded in the controller, detects the unprotected and the un-equalized cell in the battery stack and decides the detected battery to be charged or discharged according to the battery's condition. The Li-ion battery could be equalized by discharging the overcharged cell to the battery pack or charging the over-discharged cell from the battery pack. Using two fly-back DC-DC converter circuits to perform the energy transfer as a step-up converter circuit during discharging and as a step-down converter circuit during charging. The model circuit of the BCEC as a process and execution are simple and efficient. The control algorithm flow chart is shown in Figure (5).

Firstly, the controller monitors and records the battery cells' voltages and calculates their average value. Then the control function calculates the SOC of the battery according to the battery open-circuit voltage to test the condition of the battery. The algorithm detects the battery cell, which is out of the normal operating range of SOC. For protection, the control algorithm maintains the SOC difference between the battery cells to operate at 0.1% for equalization. Suppose a battery cell is detected as unprotected or unbalanced. In that case, the control algorithm simulates the MOSFET switch, converter access relay, PWM control based on an intelligent control algorithm like the fuzzy logic controller (FLC) or single sliding mode controller (SSMC) and the fly-back converter simultaneously. After a single loop of the control algorithm is completed, the controller measures the battery cells voltages, calculates the average value, and checks the



battery cells conditions, whether all are protected and equalized or not. According to the battery

Figure (4) The control algorithm flow chart

cells' condition, the controller defines the step-up converter circuit or the step-down converter circuit to be operated by PWM control based on an intelligent controller for charging or discharging when the battery cells are identified as unprotected or unequalized.

III. FUZZY LOGIC CONTROL FOR SOC-BASED EQUALIZATION

The FLC system is known for its strong robustness. Using many Li-ion batteries in E.V. to achieve the power requirements so obtaining mathematical models are hardly obtained accurately, but the parameters' changes have little influence on the system in the fuzzy controller. Using FLC doesn't require a mathematical model of the system. The FLC's primary function is to control the switching period to control the equalization current to achieve equalization. The fuzzifier converts the numerical inputs into fuzzy linguistic sets, as shown in Figure (5). After that, FLC generates the required control value according to the rule base and the inputs using the inference engine. Then the defuzzifier converts the results to the exact crisp output. Thus, the FLC rule is to achieve SOC equalization.

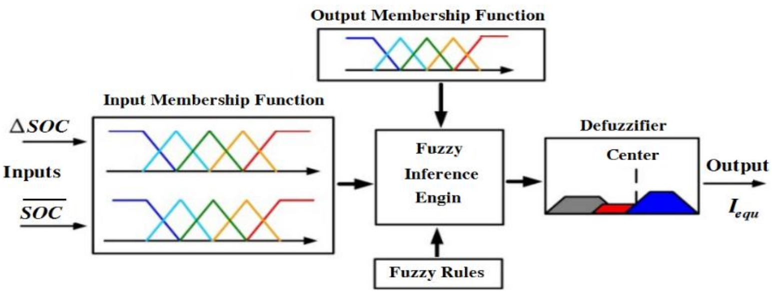


Figure (5) Block diagram of the FLC

The two inputs of the FLC are SOC differences values (ΔSOC) and SOC averages values of cells, which can be expressed as:

$\Delta SOC = Soci_i - SOC_{i-1}$ (4)

$\text{Avg of SOC} = (SOC_i + SOC_{i-1})/2$ (5)

where SOCi is the ith cell, SOCi and SOCi-1 are adjacent in the battery pack.

As the purpose of the BCEC aims to make all the cells occupy the same SOC, and as mentioned above, the BCEC depends on the difference in SOC, not the difference in cell voltages. A large ΔSOC requires a large equalization current to increase the equalization speed. On the other hand, a small ΔSOC indicates a slight imbalance, so the large equalization current isn't required in the equalization process. So, the first input determines the equalization speed.

On the contrary, the transferring equalization method used in this paper is to charge one cell at a time using the excess charge in another one. Thus, it's essential to consider the discharging ability. A large equalization current may accelerate the balancing speed, but the overlarge current may damage the discharging cell if it has a relatively low SOC. The SOC average is used to decide if a large equalization current is allowed or not. So, the SOC average is responsible for protecting the cells.

To achieve the balancing without affecting the battery safe region, the RMS value of the balancing current should not be exceeded by 8.0A for cells. In this paper, both of the FLC inputs are set as 0 to 0.3, and 0 to 1.0 respectively. Some linguistic variables express those variables. The first input's fuzzy variable is divided into very large, large, medium, small, and very small fuzzy subsets. The other fuzzy input variable is divided into large, medium, and small fuzzy subsets. The fuzzy output variable, the duty cycle, is divided into very large, large, medium, small, and very small fuzzy subsets. According to its simple calculations with excellent control performance, using the triangular membership function as shown in Figure (6).

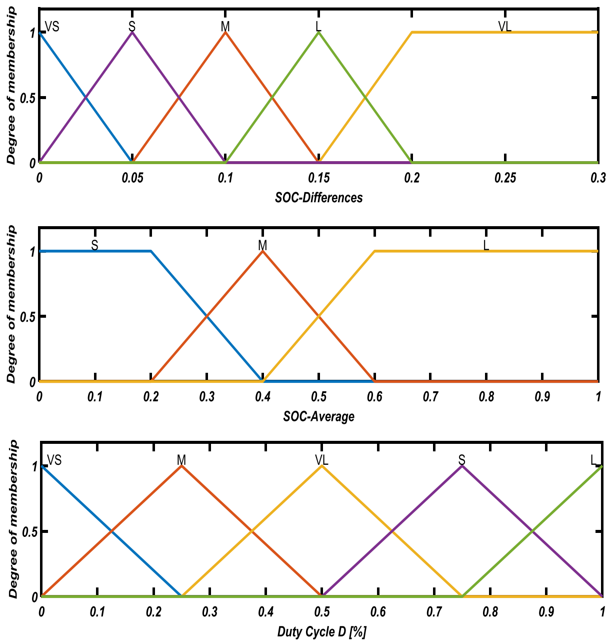


Figure (6) Input and outputs Membership functions of FLC

D		ΔSOC				
		very small	small	medium	large	very large
SOC	small	small	medium	large	very large	large
	medium	medium	medium	medium	large	large
	large	very small	small	small	small	medium

Table (1) The FLC Rule base table.

The rule base of the FLC is obtained by the experience and knowledge of battery balancing. The form of fuzzy rule is presented as follow for example: If ΔSOC is S and SOC average is S, then D is M. As mentioned above, battery experiment results obtain the fuzzy rules, and the linguistic variable table of the fuzzy rules is two dimensional (3 x 5), shown in table 1. The fuzzy inference engine role deduces the fuzzy linguistic output from the fuzzy rule base. The defuzzification process comes then converts the linguistic output to an actual value. Thus, the duty cycle is the switching period that controls the driving signal to regulate the equalization current. The defuzzification method is used in this paper is centroid defuzzification.

IV. SLIDING MODE CONTROLLER

In this paper, Using the single sliding mode controller (SSMC) to activate bidirectional cell switches and control the direct current of a chopper circuit (DC-DC flyback converter circuit) with pulse width modulation generation. According to the non-linearity of the Li-ion battery model, the parameters of the SSMC are adapted online so that global stability is achieved in any operation condition. The surface of the sliding is formed by the battery current (ib), the DC voltage error, and the integral of the DC voltage error. Thus, the controller detects the direction of the power flow either charging or discharging according to the sign of ib and the error in the DC voltage. The switching function α and sliding surface β are given in equation (6), where VR is the reference voltage and K1, K2 are the surface parameters.

$\alpha = ib + K1.\,(VR - VDC) + K2.\int (VR - VDC)\,dt$

AND $\beta = \{ \alpha = 0 \}$. (6)

The block diagram of the SSMC is shown in figure(7) where u is the MOSFET activation signal which is generated by an inverted-comparator centered in zero evaluating the switching function α.

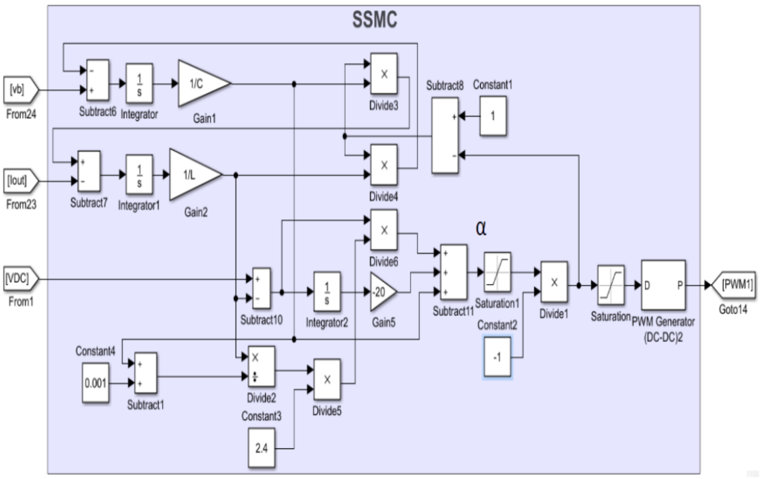


Figure (7) the sliding mode control block diagram.

We can estimate the derivative of the switching function is given in eq (7) as ΔVDC is the deviation of the DC voltage.

$$\frac{d\alpha}{dt} = \frac{dib}{dt} - K1.\frac{dVDC}{dt} + K2.\Delta VDC \qquad (7)$$

Where ΔVDC = VR – VDC (8)

As,

$$\frac{dib}{dt} = \frac{Vb - VDC.(1-u)}{L} \;,\; \frac{dVDC}{dt} = \frac{ib.(1-u) - iDC}{C} \qquad (9)$$

Thus, by substituting from eq(9) into eq(7) we obtain:

$$\frac{d\alpha}{dt} = \frac{Vb - VDC.(1-u)}{L} - K1\left(\frac{ib.(1-u) - iDC}{C}\right) K2.\Delta VDC\,. \qquad (10)$$

To ensure that the sliding mode exists, firstly guarantee that: $\alpha=0 \wedge \frac{d\alpha}{dt} = 0$ [36].

Secondly, three conditions must be ensured [37]:

a) Transversality condition:

Which analyses the presence of the control variable in the derivative of the sliding surface. To ensure the ability of the SMC to modify the system behavior [38]:

$$.\ \frac{d}{du}\left(\frac{d\alpha}{dt}\right) \neq 0$$

Deriving eq(6) with respect to u :

$$\frac{d}{du}\left(\frac{d\alpha}{dt}\right) = \frac{VDC}{L} + K1.\frac{ib}{C} \neq 0 \qquad (11)$$

If ib =0, thus null power exchange,

$$\frac{d}{du}\left(\frac{d\alpha}{dt}\right) = \frac{VDC}{L} > 0 \qquad (12)$$

Else if ib<0, thus discharging the overcharged cell, which requires K1<0 as the transversality must be positive as VDC, L, and C are positive.

Else if ib>0, thus charging the undercharged cell, then $(-K1 < \frac{VDC}{ib}.\frac{C}{L})$ must be achieved.

b) Reachability condition:

Which analysis the ability of the system to reach the surface.

For positive transversality [39], $\frac{d}{du}\left(\frac{d\alpha}{dt}\right) > 0$, thus the positive derivative of α is obtained by u=1 and the negative one is obtained for u=0. But the relation is inverse for negative transversality.

$$\lim_{\alpha \to 0^-} \frac{d\alpha}{dt} > 0 \;\; where\; u = 1 \;\;\wedge\;\; \lim_{\alpha \to 0^+} \frac{d\alpha}{dt} < 0 \;\; where\; u = 0 \qquad (13)$$

$$\text{Thus, } \frac{Vb}{L} - K1.\frac{iDC}{C} + K2.\Delta VDC > 0 \qquad (14)$$

$$\frac{Vb - VDC}{L} - K1.\frac{ib - iDC}{C} + K2.\Delta VDC < 0 \qquad (15)$$

As ib, Vb = iDC.VDC ∧ Vb =(1-d). VDC ∧ ib .(1-d)=Idc (16)

Where d represents the converter duty cycle.

Thus, we obtain:

$$\frac{Vb - VDC}{VDC}.\left(K1.\frac{iDC}{C} + \frac{VDC}{L}\right) + K2.\Delta VDC < 0 \qquad (17)$$

According to the transversality value, the term $(K1.\frac{iDC}{C} + \frac{VDC}{L})$ is positive, and to achieve a stable behavior of the system, K2 must be a negative value as mentioned before. For ΔVDC value:

ΔVDC=0, stands for the desired VDC condition.

ΔVDC>0, stands for an undershot.

ΔVDC<0, stands for an overshot.

C) Equivalent control condition:

To analyses the local stability of the system.

$\frac{d\alpha}{dt} = 0$ as: u=ueq , 0< ueq <1 where ueq is the analog equivalent value of u [37].

$$\text{Thus, } ueq = \frac{-\frac{Vb-VDC}{L}+K1.\frac{ib-iDC}{C}-K2.\Delta VDC}{K1.\frac{iDC}{C}+\frac{VDC}{L}} . \qquad (18)$$

Hence, fulfilling the reachability conditions also achieves the equivalent control condition.

$$-\frac{Vb-VDC}{L}+K1.\frac{ib-iDC}{C}-K2.\Delta VDC>0 \qquad (19)$$

$$-\frac{Vb-VDC}{L}+K1.\frac{ib-iDC}{C}-K2.\Delta VDC< K1.\frac{iDC}{C}+\frac{VDC}{L} \qquad (20)$$

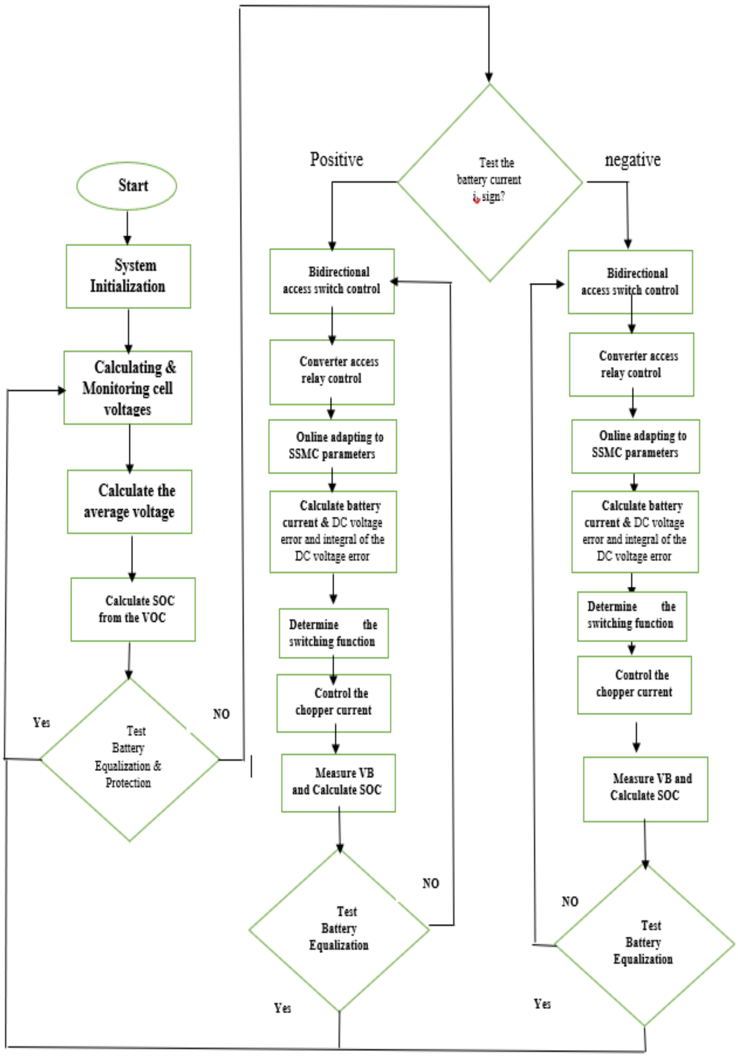


Figure (8) The control algorithm using SSMC flow chart

V. RESULTS and DISCUSSION

The proposed scheme is shown to perform the two keys per-cell functions of voltage monitoring and cell balancing required for a complete BMS. The battery module studied in this paper is composed of 3 cells. The important thing in this module is that it's easy to modify it with the specified number of cells. The equalization starts whenever a cell is detected as overcharged or over-discharged based on the normal operating voltage range between 3.72 and 3.88 V, which corresponds to a minimum ΔSOC of 0.1% for equalization testing. The simulation architecture of the battery equalization is built in MATLAB/Simulink, which consists of a data acquisition unit, SOC estimation unit, and battery equalization unit. The SOC estimation unit supplies the judgment for battery equalization. The meant BCEC has a superior balancing speed with minimum execution problems. For the battery equalization one, it is used to implement the equalization of the battery and improve the battery consistency which includes also the FLC and SSMC module. A comparison is made between the proposed scheme of BCEC based on FLC for battery equalization and the proposed scheme of BCEC based on SSMC for battery equalization with the mean-difference algorithm in the standing state as shown in Figure (9) and Figure (10) respectively. The equalization times for mean-difference algorithm, SSMC and FLC are 1974 s, 1685 s, and 1464 s respectively under the same conditions with a difference in SOC 35%, while it takes 1004 s, 847 s, and 732 s respectively under the same conditions with a difference in SOC 14%. The proposed charge equalization controller has excellent equalization speed and less execution trouble. The FLC improves the equalization times compared with the mean-difference algorithm in the standing state and the SSMC algorithm.

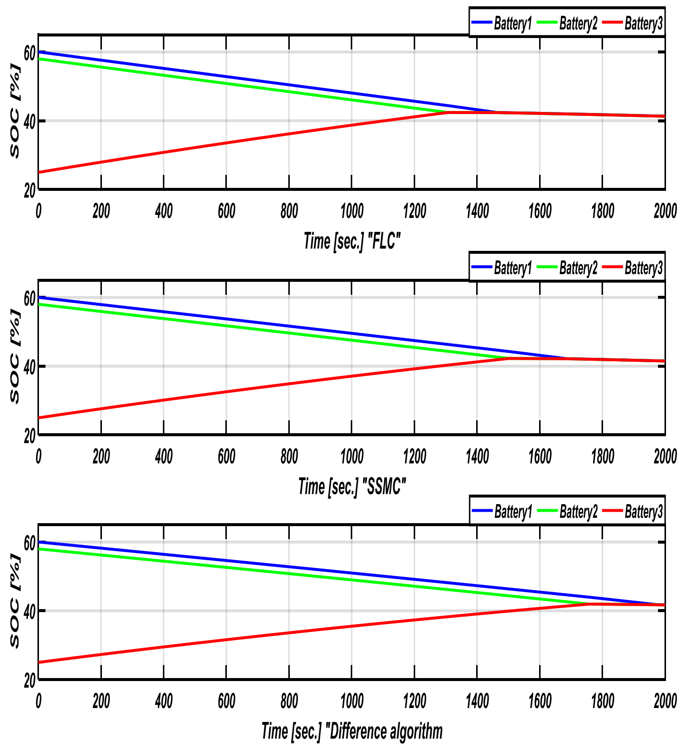


Figure (9) The balancing times for the FLC, SSMC, and the mean difference algorithm with a difference in SOC 14%.

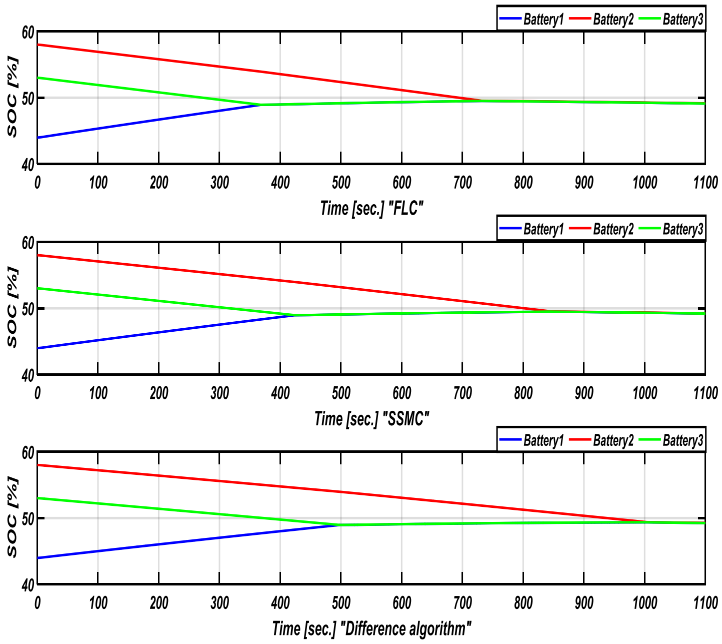


Figure (10) The balancing times for the FLC, SSMC, and the mean difference algorithm with a difference in SOC 35%.

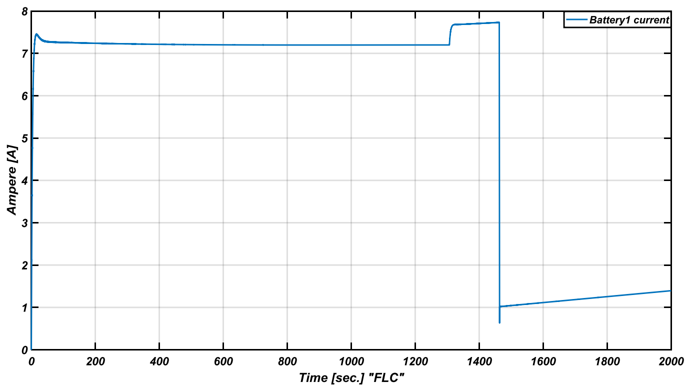
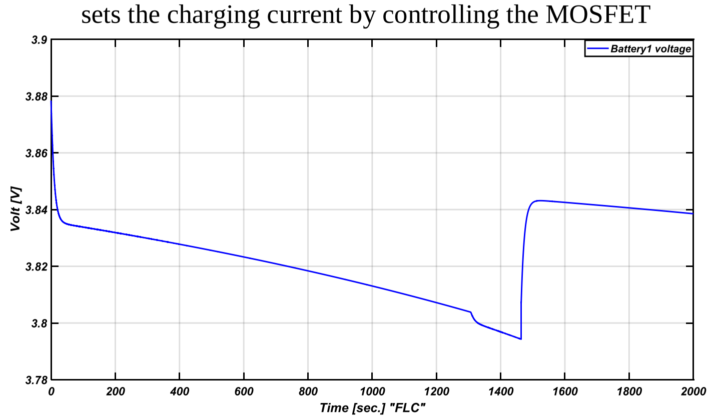


Figure (11) Battery cell's no. two current with a difference in SOC 35% based on the FLC algorithm.
Figure (12) Battery cell's no. two voltage with a difference in SOC 35% based on the FLC algorithm.

The second battery cell's current and voltage based on the FLC for the difference in SOC 35% are shown in Figure (11) and Figure (12) respectively. The controller sets the charging current by controlling the MOSFET



switch with PWM to charge the lowest SOC's cell until the equalization between cell two and three is achieved, then the controller modifies the current according to the SOC difference between the battery cells as shown.

VI. CONCLUSION

In this paper, a non-dissipative BCEC based on fuzzy logic control FLC algorithm is presented with the same BCEC scheme based on SSMC algorithm for battery equalization charging was presented. The bidirectional equalization circuit with energy transferring capacitor inductor is used to improve and develop the inconsistency of n cells of series-connected Li-ion batteries, and the cell-to-cell technique is chosen to achieve the equalization. The SOC-based equalization is selected for the battery equalization. The BCEC is based on FLC or based on SSMC, which is designed and implemented to control the equalization current by controlling the switching period of the driving signal. A comparison between the proposed scheme which is based on FLC with mean difference algorithm and the SSMC algorithm is carried out to validate the advantages of the BCEC based on FLC. Simulation results show that the BCEC based on FLC saves the equalization time under the same equalization conditions compared with the other algorithms, so it reduces the energy consumption and improves the inconsistence of the battery.

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